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Highlights

- The Port Askaig Formation contains 47 diamictites and shows a pattern of gradual evolution upsection of lithologies of the diamictites, of the interbeds and of clast types.
- The diamictites are interpreted as tillite and their basal surfaces are almost always sharp, recording the change from non-glacial to glacial environments.
- The tops of diamictites often preserve a detailed record of glacial to periglacial to non-glacial environments (sandstone wedges, frost shattered clasts, cryoturbations).
- The formation records 28 glacial, 25 periglacial and 23 non-glacial episodes.
- Parts of Members 1 and 2 on the east of Garbh Eileach are more complete than elsewhere.
- The Argyll Group, from the PAF to the Jura Quartzite, shows huge thickness (7km) in the Garvellachs area: accommodation space was created continually and at a fast rate.
- A comparison of the PAF with other thick, relatively complete Phanerozoic and Cryogenian glacial successions suggests that the PAF is exceptional in its combination of formation thickness (ca. 1100 m), the number of climatically-related stratigraphic episodes (76) and the huge thickness of the Neoproterozoic succession within which it lies.

- The completeness of the PAF stratal record is supporting evidence that the base of the PAF in the Garvellach Islands is a succession without a major break and supports it being a candidate for the Cryogenian GSSP.

Abstract

The Port Askaig Formation (PAF) is a diamictite-bearing succession in the Dalradian Supergroup of Scotland that provides an excellent archive of a Cryogenian glaciation in the Garvellach Islands and Islay, Argyll. The formation is ~1100 m thick, comprises 5 members and includes 47 diamictite beds, interbedded with siltstones, dolostones and sandstones. Here we document seven features of the PAF that indicate its relative stratigraphic completeness. There are gradual, progressive changes up-section in the lithologies of the diamictites, their interbeds, and clast lithologies. The sharp basal surfaces of the diamictites each show the same, repeated pattern of environmental change, from non-glacial to glacial. Many of the top surfaces of the diamictites show evidence of periglacial conditions. The succession in the PAF records a total of 76 climatically-related stratigraphic episodes: 28 glacial episodes, 25 periglacial episodes and 23 non-glacial episodes. Parts of Member 1 (Diamictites 1 to 12 and Diamictites 16 to 18) and Member 2 (Diamictite 31 to the base of Member 3) are most compete on the east coast of Garbh Eileach. The PAF in the Garvellach Islands occurs within a succession that is several kilometres thick, as newly revealed by sea-floor mapping. Compared with other Cryogenian and Phanerozoic glacial successions, the PAF is exceptional in its combination of formation thickness, the number of climatically-related stratigraphic episodes, and the considerable thickness of its host supergroup. Furthermore, these indicators of relative stratigraphic completeness provide evidence that the base of the PAF on the east coast of Garbh Eileach is a succession without a major break in deposition, supporting the account of the strata at and below the base of the PAF in the companion article by Fairchild et al. (this volume).

1. Introduction

This paper provides the first detailed analysis of ‘indicators of relative stratigraphic completeness’ in a Neoproterozoic glacial succession. These ‘indicators’ allow us to re-affirm that the Port Askaig Formation (PAF) in the Garvellach Islands is a succession containing an exceptional archive of climatically-related depositional episodes. Our main aim, however, in the context of this special issue on the Tonian-Cryogenian boundary, is to show that they are entirely consistent with the inferred lack of a stratigraphic break at the base of the formation (Fairchild et al., this issue). Thus they add to the case presented in that companion article - that the rock succession of the Garvellach Islands is a candidate to host the basal Cryogenian Global Boundary Stratigraphic Section and Point (GSSP).

The Port Askaig Formation occurs near the middle of the ca. 25 km thick Dalradian Supergroup, a largely Neoproterozoic succession which may extend upwards into the Early Cambrian (Stephenson et al. 2013). The stratigraphic position of the PAF in the Dalradian and as a representative of the Sturtian glaciation in the Cryogenian System is shown in Fairchild et al. (this volume, their fig. 2). It crops out at approximately 30 localities from western Ireland to northeast Scotland and is generally between 100 m and 500 m thick but is thickest, least metamorphosed and deformed and best preserved in Argyll, where it is ~1100 m thick (Fig. 1). There the complete succession has been established by mapping around Port Askaig, on Islay, but the finest outcrops are in the Garvellach Islands, where the combination of a raised rock platform and a uniform dip continuously expose 550m of strata (Fig. 2).

A glacial origin for granite-boulder-bearing strata at Port Askaig was suggested by Thomson (1871) – making this the first Cryogenian glacial deposit to be recognized. The remarkable nature of the stratigraphy was first revealed by Kilburn et al. (1965), who measured the section in the Garvellachs, recognizing 38 diamictite beds. A comprehensive study of the Garvellachs and Islay was reported by Spencer (1971), who recognized five members and a total of 47 diamictite horizons in the ~1100 m-thick PAF; this succession was interpreted to record 17 glacial episodes, 27 periglacial episodes and 17 non-glacial periods. The latter author recognised the same 38 diamictite beds as Kilburn et al. (1965) and added a further nine; in this study, we follow this nomenclature, and abbreviate accordingly (e.g. Diamictite 1 is abbreviated to D1). Study of the Garvellach outcrops was next reported in a series of papers in which the diamictites were interpreted to have arrived as material from floating ice and down-slope mass flows (Eyles & Eyles 1983; Eyles & Clark 1985; Eyles 1988; Arnaud & Eyles 2002). Benn & Prave (2006) produced new evidence for glaciotectonic deformation in the Garvellachs, and new fieldwork there in the last five years – by most of the authors of this article - has added greatly to the evidence for grounded ice and emergent conditions. This article outlines some of these new data but full accounts will be published in a planned, comprehensive memoir. We do not discuss the full palaeoclimatic implications of the PAF here or its relevance to the Snowball Earth hypothesis.

One aspect of the succession has not been made clear in previous publications: the significance of the many 'indicators of relative stratigraphic completeness' that are present. In this article we aim to document seven types of 'indicators': (i) that the overall stratigraphic pattern of the formation shows gradual, progressive changes in the lithologies of the diamictites and the interbeds and of the clast types: (ii) that the basal contacts of the diamictites each show the same, repeated pattern of environmental change; (iii) that the top surfaces of most of the diamictites show consistent patterns of detailed environmental change, from glacial to periglacial to non-glacial conditions; **(iv)** that the succession in the PAF records a total of 76 climatically-related stratigraphic episodes; (v) that the east coast of Garbh Eileach – where the base of the PAF is best exposed – shows a thicker and more complete succession at three separate stratigraphic levels; (vi) that the PAF in the Garvellach Islands occurs within a succession that is several kilometres thick, as now shown by new sea-bed geological mapping; and (vii) that, at the largest scale, the PAF and the major part of the enclosing Dalradian Supergroup are amongst the thickest Neoproterozoic successions anywhere. The seven 'indicators' show that the PAF succession is stratigraphically more complete on the east coast of Garbh Eileach – compared with exposures to the west - and contains a record of climatically-related stratigraphic episodes which is exceptionally rich when compared to other Cryogenian and Phanerozoic glacial successions.

2. Overall stratigraphic pattern

The diamictite beds in the Garvellachs were numbered 1 to 38 by Kilburn et al. (1965, their fig. 3) and they marked there the gradual upward change in clast types, from carbonate fragments to granite fragments. Spencer (1971, plate 10) erected five members in the formation: members 1-3 in the Garvellachs and members 4-5 on Islay, which contained a further 9 diamictites, making 47 in total (labelled D1 to D47 in this article).

The lithological composition of the matrix of these 47 diamictites changes progressively upwards through the PAF. In Member 1 they are dolomitic siltstones (Fig. 3, D7, D15); in Member 2 they change from sand-rich dolomitic siltstones (D19-22) to dolomitic, silty arenites (D26, D29); in Member 3 (D35, D38) and Member 4 (D40, D42, D45) they are silty arenites. Modal analyses showing these changes are given in Spencer (1971, fig. 28b).

The gradual upward change in clast types was also noted by Spencer (1971, plate 10), expressed then as "the ratio of dolomite to granite stones". New, systematic, measurements of clast type have been made, by counting stones larger than 1cm in a 50 x 50 cm square and marking their outlines onto tracing film. Seven clast types have been counted: dolomite, limestone, intrabasinal unknown, granite, quartzite, extrabasinal unknown and unknown. Here we illustrate the extrabasinal clasts (i.e. granite + quartzite + extrabasinal unknown) (Fig. 4), which show there is a steady, progressive change in clast types upwards through the PAF. In the lowest diamictites of Member 1, only intrabasinal clasts are present (Fig. 3, D7). Extrabasinal clasts first become predominant towards the top of Member 2 (Fig. 3, D29). At the top of Member 4 there are almost no intrabasinal clasts (Fig. 3, D42). The percentages of the seventh clast type ('unknown') are small and do not affect the trend shown in Fig. 4 (0% unknown in 106 measurements; 1-10% in 50; 11-20% in 15; 21-42% in 13).

The stratified sedimentary rocks separating the diamictites show a similar, progressive, upward change in lithology, from dolostones to white sandstones. Beds of dolostone are only present in members 1 and 2 (Fig. 2). The sandstone interbeds are dolomitic in members 1 and 2, but more arenaceous in Member 3 and highly arenaceous in Member 5; modal analyses showing these changes are given in Spencer (1971, fig. 28a). These lithological trends of the stratified sedimentary rocks in the PAF fit with the overall litho-stratigraphic progression of the formations in this part of the Dalradian Supergroup, from the carbonate rocks of the Lossit Limestone and Garbh Eileach formations up to the monotonous sandstones in the Jura Quartzite; only the Bonahaven Dolomite interrupts this uniform progression.

2.1. Isotope data

Further insight into the progressive changes represented by the succession is provided by carbon isotope analyses of clasts of dolomite (common) and limestone (rarer) in the basal diamictite units. These analyses were made as part of a wider study (Fairchild et al., this issue) which established that the $\delta^{13}C$ values in the studied section were virtually unaffected by diagenetic and metamorphic change. The clasts are lithologically similar to the underlying Appin Group succession, 70 m of which is exposed on Garbh Eileach (Fig. 5). This succession is described in detail in Fairchild et al. (this issue) and there re-named the Garbh Eileach Formation (GEF); it was formerly called the Islay Limestone. It is younger than the sub-PAF Lossit Limestone of Islay. The GEF broadly consists of microsparry limestones and dolomicrites, locally interlaminated and typically containing siliciclastic impurities. Lithologies become consistently dolomitic upwards and contain siliciclastic sand. Carbon isotope characteristics of dolomite and limestone beds from similar horizons are indistinguishable and define a distinct negative anomaly, the *Garbh Eileach anomaly*, which passes smoothly up into $\delta^{13}C$ values close to zero above the 60 m level (Fig. 5). Bedded dolomites are also found between some of the lower diamictite beds and have similar lithological and carbon isotope characteristics to those at the top of the GEF. Evidence for gypsum formation and for ice-rafting is found in both the topmost GEF beds and up to the base of D2 in the PAF, indicating an overall environmental transition at the base of the PAF, despite the sharp bases of individual diamictite beds.

Specific evidence of erosion of the lateral equivalents of the underlying succession is found in the Great Breccia where rafts of sediment, up to tens of metres across, include those with an internal stratigraphy that can be closely matched with sediments across the GEF-PAF boundary (Fairchild et al., this issue). Erosion of the lateral equivalents of immediately underlying strata is also indicated by the identical $\delta^{13}C$ values of dolomite clasts in the basal two diamictites (Fig. 5). Clasts in higher diamictites display a wider range, including many dolomite clasts with values as low as -3 ‰ which must be sourced at deeper levels of erosion. Although limestone clasts are much rarer, a minimum of five were analyzed from each of several diamictite beds. They display consistently negative $\delta^{13}C$ values with gradual shifts in mean composition from a minimum of around -4 ‰ to a value close to zero in D12 (Fig. 5). Comparison with the underlying GEF shows little overlap with the -4 to -7 ‰ values of the exposed Garbh Eileach anomaly, so derivation from limestone beds forming the lower, descending limb of the anomaly at deeper erosional levels is implied. Since the next oldest exposed strata (on Islay) have weakly positive carbon isotope signatures (Fairchild et al., this issue), it is logical to interpret the values around zero in limestone clasts in D12 as indicating that erosion reached limestone beds beneath the Garbh Eileach anomaly.

3. **Basal surfaces of diamictite beds**

Almost all diamictites in the PAF have sharp bases on dolomites, siltstones and sandstones. None of the diamictites have gradual, transitional bases and no examples have been observed where stratified sedimentary rocks lacking clasts pass gradually upwards, through stratified sedimentary rocks with clasts, into stratified diamictite and finally into unstratified diamictite. Also, none of the basal surfaces of the diamictites show angular discordance or erosional geometries. Instead the basal surfaces are always parallel with the layers of the strata below. These sharp basal contacts – and the lack of gradual transitions - were first noted by Kilburn et al. (1965, p. 351) and highlighted by Spencer (1971, p. 11), but were not emphasized by subsequent observers (e.g. Eyles & Eyles 1983; Eyles 1988; Arnaud & Eyles 2006).

Figure 6 shows selected examples of well-exposed, sharp basal contacts of the diamictites observed throughout members 1 to 3 in the Garvellachs. In Member 3, the diamictites overlie tidal sandstones (Fig 6 a-c). The sandstones lack any clasts and the diamictites are massive. In places, the topmost metre of the sandstone has poorer stratification (but normally no clasts); in places, the lowest metre of the diamictite has homogeneous sandstone lenses with few clasts (e.g. Spencer 1971, his fig. 3), but mostly the basal contacts of these diamictites are knife-sharp. In Member 2, D30 has a sharp base (Fig 6 d). D23 is laminated and contains sparse outsized stones which may represent ice-rafted debris (IRD). Nevertheless, it has both a sharp base and a sharp top beneath the unstratified D24 (Fig. 6 e).

As has been noted by all observers in the Garvellachs, the basal contacts of the diamictites normally show no evidence of glaciotectonic disturbance (e.g. Fig 6 f). However, recent observations suggest that there are subtle, small-scale, disturbance structures whose significance may have been overlooked (e.g. Spencer 1971, his figures 3, 6 b, c, f, g). Here we illustrate another example: the dolomite breccia present at the base of D19, which appears to be composed of ripped-up fragments of the Upper Dolomite (Fig 6 g). Note, however, that the base of D19 in an exposure 2 km farther west shows no signs of glaciotectonism (Fig. 6 h).

These sharp basal contacts to the diamictite beds must record abrupt changes from non-glacial to glacial conditions. That such contacts are repeated at least 25 times in the PAF implies that such switches occurred - and were preserved - at least 25 times.

4. Top surfaces of diamictite beds

The top surfaces of the diamictite beds in the PAF are also sharp, but exhibit many more depositional structures than the basal surfaces. Involution structures and polygonal wedges in the tops of the diamictites were first recognized by Kilburn et al. (1965, their fig. 4). These were illustrated and documented by Spencer (1971), who recognized many levels of “sandstone downfolds” and recorded sandstone wedges at 27 horizons, interpreting the latter as periglacial structures. This interpretation was disputed by Eyles & Clark (1985), who argued more evidence was required to invoke a periglacial origin. New fieldwork has, we believe, provided this evidence and will be published in full elsewhere. Here we illustrate some examples of the depositional structures of the top surfaces of the diamictites, because they provide some of the best data on the repeated preservation of detailed environmental changes.

Frost-shattered clasts have been found at six stratigraphic levels in members 2 and 3 in the Garvellachs (Fig. 2); five of these are at the tops of diamictites. Coarse-grained granite clasts, up to boulder size, have been seen which appear to have disintegrated *in situ*, with the gaps between the fragments filled with the normal diamictite matrix (Fig. 7 a). At other levels, quartzite clasts appear to have shattered into angular fragments, with normal diamictite matrix between the separated parts of the clast (Fig 7 b); this photograph also shows angular quartzite debris to the right of the clast. These newly discovered frost-shattered clasts provide the supporting evidence for periglacial conditions.

The “sandstone downfolds” of Spencer (1971) have been re-studied and three levels are now interpreted as periglacial cryoturbations (Fig. 2). One of these (Fig 7 c) affects sandstones at the top of D26. This exposure is sketched in Fig. 8 a, which also shows the detailed stratigraphic column 2 km to the west (Fig. 8 b); there the cryoturbated horizon contains frost-shattered clasts and is 5 m above the top of D26.

The sandstone wedges have been re-studied and are now confirmed at 23 stratigraphic levels, 18 of which are in the tops of diamictite beds. The best developed polygonal system of wedges is in the top of D22, on the west coast of Eileach an Naoimh (Fig. 7 d). On the east coast of the island, one kilometre away, polygonal wedges are again exposed at this horizon (Fig. 7 e) and are there associated with a thin breccia bed containing angular fragments, mostly of quartzite (Fig. 7 f). Sandstone wedges also occur penetrating stratified sedimentary rocks (Fig. 7 g). A general observation in cross-section is that the tops of the wedges are always truncated at erosion surfaces, commonly beneath lag conglomerates (Fig. 7 g, h). In one exceptional case, a system of polygonal wedges is truncated beneath a thin overlying diamictite bed (Fig. 7 i).

Four conclusions can be listed with respect to these features at the tops of diamictite beds. Firstly, they show that many detailed events are preserved in the rock record (e.g. Fig. 8), at numerous horizons (Fig. 2). Secondly, the association of sandstone wedges, frost-shattered clasts and cryoturbations records periglacial environments transitional between the (glacial) diamictites and the succeeding (non-glacial) stratified sedimentary rocks. Thirdly, they imply that any erosion was minor. Fourthly, taking the record of these periglacial horizons in the PAF as a whole, such conditions are preserved at 25 levels in the ca. 1100 m thick-stratigraphic column (Table 1).

5. Climatically-related depositional episodes

The diamictite bed numbers 1 to 38 of Kilburn et al. (1965) were assigned by W. S. Pitcher and R. M. Shackleton when they measured the section on the east and south coasts of Garbh Eileach in 1962. All subsequent authors have retained and built on this numbering system (e.g. Spencer 1971; Eyles & Clark 1985; Arnaud & Eyles 2006). Nevertheless, some of the beds that Pitcher and Shackleton measured between the numbered diamictites are only centimetres thick and have been shown to be absent laterally (Spencer 1971, plate 11a). Clear examples in the Garvellachs where the numbered diamictites are best grouped together are: D14-15, D19-22, D27-29, D33-35, D37-38. Some of the diamictites in Member 4 on Islay are also best grouped together.

The PAF succession consists of diamictite beds containing far-travelled clasts, alternating with beds of sandstone, siltstone and dolomite which lack such clasts. Using the diamictite groups, most of which are shown on Fig. 2, we have tallied three types of episode represented in the PAF: glacial, periglacial and non-glacial (Table 2). Diamictites 1 to 12 are there treated as one group, but require further study. The 26 diamictite groups, plus two beds of laminated siltstones with ice-rafted debris (IRD) in Member 2 (one shown in Fig. 7 g), add up to a total of 28 glacial episodes. The horizons with periglacial features total 25. These glacial plus periglacial episodes are separated by 23 non-glacial episodes. Thus in the ~1100 m of strata of the PAF there are a total of 76 climatically-related depositional episodes preserved.

6. Relative completeness of east Garbh Eileach section

The stratigraphic section of members 1 and 2 on the east coast of Garbh Eileach is the most complete in the Garvellach Islands. It is also the most accessible and the easiest in terms of terrain because it is exposed on a continuous raised rock platform. Recent work has shown that this section preserves the most episodes, with extra strata (when compared with other sections in the Garvellachs and Islay) present at three levels: in the lowest and uppermost parts of Member 1 and in the uppermost part of Member 2.

Sedimentological evidence presented in Fairchild et al. (this issue) indicates that there is an environmental transition at the base of the PAF, with dolomites locally containing gypsum pseudomorphs (arid tidal flat environment) that are interstratified with sediments with IRD (shallow water environment liable to ice-rafting); the first diamictite (D1) occurs within this transition zone. In that paper, the smoothly varying nature of the carbon isotope profile from the Garbh Eileach Formation and upwards into D1 and D2 (on both Garbh Eileach and Dun Chonnuill) is viewed as consistent with the apparently conformable contact between the two formations. Herein, we also show that the carbon isotope composition of limestone clasts from D1 to D12 show smooth changes over 100 m of stratigraphic height (Fig 5), also consistent with a lack of significant stratigraphic breaks within this interval. It should be noted that D1 to D12 are only present in the Garvellachs (Fig 9). On Islay, where D1 to D12 are missing, conglomeratic sandstones (traditionally labelled the 'Great Breccia') overlain by Disrupted Bed lithologies, rest erosionally on underlying pre-glacial carbonates (Spencer, 1971; Fairchild et al., this issue). In the Garvellachs, the interval from the top of the Great Breccia to the base of the Disrupted Beds consists dominantly of arenites and conglomerates composed largely of detrital dolomite. Such lithologies are atypical of the PAF as a whole and may reflect a discontinuous record of sedimentary events.

New fieldwork has revealed more details of the stratigraphic relationships at the top of Member 1. Spencer (1971, plate 11a) inferred an unconformable relationship between D18 and the overlying Upper Dolomite on Garbh Eileach. These strata have been followed in detail across the island (Fig. 10), revealing that the base of the Upper Dolomite is indeed an unconformity. Beneath it, the 18 m of strata from D18 down to D16 on the east coast are progressively cut out by subcrop towards the west.

Similar work at the top of Member 2 on Garbh Eileach was undertaken to check the unconformable relationship beneath Member 3 shown by Spencer (1971, plate 11a). This new investigation has confirmed that 20 m of strata, present on the east coast from D31 up to the top of Member 2, are progressively cut out by subcrop beneath the sandstones of Member 3 over a distance of 1.5 km to the west (Fig. 11).

These three intervals show that more stratigraphic units are preserved in the outcrops on the east coast of Garbh Eileach than further to the west. If we express this in terms of the 'depositional episodes' of the previous section, then the east coast section contains four more diamictite episodes (D1 to D12, D16-18, D31, D32) and four more periglacial episodes (wedges above D18, D31, D32 and above the overlying 'rhythmically laminated siltstones'). These eight episodes amount to about 10% of all of the 76 'depositional episodes' present in the whole of the PAF. This is a direct indicator of the relative completeness of the stratigraphic section on the east coast of Garbh Eileach.

7. Accommodation space and subsidence.

In comparison with other Neoproterozoic glacial successions, the PAF in the Islay-Garvellachs region of Argyll is unusually thick (Fig. 13). As both under- and overlying formations were deposited close to sea level, its total thickness of ~1100 m must be close to the amount of tectonic subsidence experienced during its deposition. Assuming that the boundaries of the formation are defined by the same climatic changes that were responsible for defining other Sturtian glacial units, then the unique character of the PAF is a consequence of what, for Neoproterozoic glacial deposits, was a fortuitous tectonic context.

The PAF lies near the middle of the thick Neoproterozoic part of the Dalradian succession that was deposited in a continental rift, within the supercontinent of Rodinia, which eventually split apart and became a passive margin to the expanding Iapetus Ocean (Daly 2009). Such rift environments can produce thick successions accommodated by rapid subsidence as compared with continental interior or cratonic regions. However, these successions are commonly strongly deformed and metamorphosed, as their eventual position at continental margins means that they inevitably become involved in subsequent plate collisions. Although the Dalradian Supergroup was deformed during the Grampian Orogeny in early Ordovician times, it escaped the intense deformation, at least in the Garvellachs/Islay area, that would have obliterated the exquisite depositional features discussed above.

Below the PAF lies the Appin Group, which on Islay and in the Appin area (40 km NE of the Garvellachs) comprises ca. 7 km of largely shallow marine sediments. Only the top of this succession is exposed on the Garvellachs, the deeper levels underlying the sea bed to the NW (Fig. 12). Above the PAF lies the Bonahaven Formation, also well exposed on Islay but lying offshore to the SE of the Garvellachs. Above this is the Jura Quartzite (Fig. 1b), a shallow-marine sandstone deposited under tidal and storm conditions that reached a remarkable 5.3 km in thickness (Anderton 1976). Although it shows lateral and vertical facies variations, nowhere does it show evidence of having been deposited either above sea level or at depths greater than a few tens of metres (Anderton 1976). The coarseness of the formation necessitates that a large amount of finer sediment was bypassed across the Jura Quartzite shelf into deeper, lower energy environments. The abundant supply of sediment, presumably transported from distant sources by large rivers, was effectively dispersed by shelf processes so that any tectonically produced accommodation space was constantly filled. For such a thick, relatively uniform succession to accumulate, the palaeogeography responsible for creating this transport system must have persisted for a remarkably long time. One can make the same argument about subsidence for the PAF. The sediment supply was more than adequate to fill the accommodation space and the shallow marine dispersal system that reworked the area returned the environment to near base-level between each glacial episode.

It seems likely that during the period from the deposition of the Appin Group through the PAF to the end of Jura Quartzite times, the area around the Garvellachs was undergoing steady, moderately fast subsidence. Sediment supply was capable of filling the resulting accommodation space and shallow marine dispersal systems distributed the sediment so that it did not, in the long term, build up above base level. During PAF times, the situation would have been complicated by eustatic sea-level changes and ice-loading; however, the interaction between subsidence, sediment supply and dispersal kept the position of the sediment surface within a few tens of metres of sea-level during the period from well before to well after PAF times.

Although data on the timing of Dalradian events is sparse, some inferences can be made about subsidence rates. The lower three groups in the Dalradian Supergroup (the Grampian, Appin and Argyll Groups) span about 200 Ma, based on an estimated age for the base of the succession at around 800 Ma (Noble et al. 1996) and the ca. 600 Ma date for the Tayvallich Volcanics (Dempster et al. 2002) (Fig. 1b). Together, these three groups are around 20-25 km thick which gives a long-term subsidence rate of 100-125 m/Ma, a figure that is typical for sediment accumulation rates measured over millions of years (e.g. Partin & Sadler 2016). Such a subsidence rate would suggest a duration of ca. 10 million years for the Port Askaig Formation.

8 Comparison with other glacial records

Here we give lithostratigraphic information on other thick, relatively complete, Cryogenian and Phanerozoic glacial successions to compare with the PAF. We have used comprehensive compilations as the main sources of information on pre-Pleistocene successions (Arnaud et al. 2011; Hambrey & Harland 1981).

8.1. Cryogenian successions

The 59 chapters in Arnaud et al. (2011) describe glacial successions of Neoproterozoic age to compare with the PAF in respect of thickness and relative completeness. Many successions rest unconformably on basement rocks (18 chapters) and so are quite different from the PAF. Other chapters have insufficient thickness data. For the remaining 32 chapters the thickness data are plotted in Figure 13. The 16 thickest sections are named and are the principal examples that bear comparison with the PAF.

The Port Askaig Formation forms part of the thickest Neoproterozoic succession; only seven others are thicker than 10 km (Fig. 13 b). Also, the formation has the third largest sub-tillite Neoproterozoic thickness, only exceeded by those in NW Tasmania and East Greenland (Fig. 13 a). Many glacial successions exceed the Port Askaig Formation in thickness (Fig. 13 b) but some of these include more than one tillite formation. Just considering the ‘basal’ tillite unit (Fig. 13 a), there are five localities thicker than the PAF and which have >10 diamictite beds. These are as follows (thickness; number of diamictites; figure number in Arnaud et al. 2011): Yangtze region, 2.7 km, approximately 14, fig. 32.2A; Macaúbas Group, Brazil, 2.2 km, approximately 22, fig.

49.5; East Tianshan, 1.7 km, approximately 12, fig. 33.7; Lena River, 1.1 km, approximately 17, fig. 27.3; Mackenzie Mountains, 1.0 km, approximately 30, fig. 36.3 . In addition, two other localities, which are not shown on Fig. 13, are thicker than the PAF and have many diamictite beds: Oman, <3 km, 9, fig. 20.1; Southern Canadian Cordillera, <2.5 km, approximately 31, fig. 37.4. The Oman succession rests unconformably on basement rocks.

These seven successions, which range from 1.0 km to 3.5 km in thickness and contain from 9 to approximately 30 diamictite beds, are most similar to the PAF but, so far, none has been shown to contain so many climatically-related depositional episodes as the latter (Table 2 – 76).

As an illustration of the difficulties in assessing the number of depositional / climatic episodes for the seven successions, we provide a brief account of another thick example. In the Death Valley area of California, multiple outcrop belts of Cryogenian strata occur. Correlation between them is challenging, and it is difficult to determine which, if any, of them is representative of the entire glacial record. Miller (1985) proposed a two-fold glaciation in the Panamint Range, and the separation of these by non-glacial carbonate rocks led Prave (1999) to propose that this range contains the full record of two rift-related (Sturtian and Marinoan) glaciations. This succession, which is up to 1200 m thick (Miller, 1985) was thus posited to be the most complete in the Death Valley area (Petterson et al., 2011). The diamictites rest with sharp contact on the underlying Beck Spring Dolomite (Petterson et al., 2011). However, other outcrop belts have subsequently been shown to be thicker, including the 2500 m-thick southern Kingston Range transect (Le Heron et al., this volume), and the almost 1400 m-thick interval in the Silurian Hills (Le Heron et al., 2017). This latter mountain range also contains an excellent record of a mixed siliciclastic-carbonate preglacial shelf system (Smith et al. 2016), where field observations suggest that there is a probable gradational relationship between the pre-glacial deposits and diamictites of the syn-glacial interval (Kupfer, 1960; Basse, 1978). If correct, this relationship may, like the PAF succession, imply an excellent and full record of events preserved in the overlying succession.

8.2. Cenozoic and Palaeozoic successions

Contemporary analogues for the PAF should be sought in modern rift basins with thick glacial sequences. Few such settings exist, but we identify two possible analogues.

Firstly, in the West Antarctic Rift System of the Ross Sea region of Antarctica, scientific drilling has achieved outstanding (>95%) core recovery and allowed detailed multi-disciplinary studies (Hambrey et al. 2002; Barrett 2009; Wilson et al. 2012). Three programmes – CIROS in the 1980s, CRP in the 1990s and ANDRILL in the 2000s – have yielded a proximal record of glaciations with sequences on the order of a kilometre thick and spanning up to 34 million years. The records demonstrate glacial processes at the marine-terrestrial transition and are temporally complete for large parts of the Cenozoic. The facies associations, thicknesses and cycles cored resemble those of the PAF.

The principal similarities are:

(i) The presence of numerous diamictite beds, including 49 in the 702 m CIROS 1 core, the main ones being shown in Fig. 14 (Barrett, 1989); and over 50 in the 1285 m deep AND-1B core (Wilson et al. 2012).

(ii) Sequence boundaries or "glacial surfaces of erosion" (GSE) at the base of many diamictite units (Fielding et al. 2000; Naish et al. 2001).

(iii) Strong evidence for grounded ice, notably glaciotectonically deformed layers occurring below diamictites, micromorphological investigations of thin sections of diamictites and evidence for shearing within them. In addition, there are strong clast orientation fabrics. This evidence leads to the interpretation of this facies being a basal till (Hambrey et al., 2002; Barrett 2009, Wilson et al. 2012).

(iv)A lack of angular stones in diamictite, indicating ice sheet-scale glaciation with most glacial sediment produced at the ice/bed interface (Hambrey et al., 2002; Barrett 2009, Wilson 2012).

(v) distinct depositional cycles, each 10-25 m-thick in the AND-1B core and comprising, from bottom to top: a glacial surface of erosion, massive diamictite, stratified diamictite, stratified sand, diatomite. These cycles indicate transitions from grounded ice to glaciomarine, then open marine conditions and are believed to be orbitally controlled (Naish et al. 2001; Wilson et al., 2012)

Barrett (2009) further analysed the proportions of facies and thickness of the cycles in CRP-1 and -2A using the high-resolution chronology that has been obtained from these cores. Focusing on the interval from 33 to 17 Ma, grounded ice extended across the CRP-2A drill site over 50 times, producing significant unconformities at 29 Ma (443 metres below sea floor (mbsf), 25 Ma (307 mbsf) and 23 Ma (130 mbsf), as well as multiple less pronounced GSEs. Such data are an indication of time intervals and sedimentation rates that are realistic for deposition of the PAF.

A second example is the long Plio-Pleistocene record, with many diamictites, preserved at Tjørnes in northeast Iceland, which resulted from subsidence adjacent to the Mid Atlantic Ridge (Eiríksson 2008). This 600 m thick sequence records 14 glaciations with terrestrial glacial deposits interbedded with lavas and tuffs.

Are there thick Palaeozoic glacial successions with lithostratigraphic patterns comparable to the PAF? Of the 52 chapters in Hambrey & Harland (1981) describing Permo-Carboniferous tillites, many have sections which are thin and rest unconformably on older rocks, commonly striated basement. Only nine chapters described thick tillite-bearing sections, ranging from 500 m to 2500 m (papers A10, B14, D4, D11, G7, G9, G12, G14, G15 in that volume), and of these only one has more than 10 diamictites: the Carnarvon Basin in Western Australia (D4), where mapping of the desert outcrops has suggested that the succession is 1250-2500 m-thick, contains 20-25 diamictites and records 4-5 glaciations (van de Graaff 1981). For the Ordovician glaciation there are 17 chapters in Hambrey & Harland (1981). Again many of the sections are thin and have tillites resting unconformably on older rocks. Two chapters have thicker sections: the Amazon region of Brazil which is 650 m-thick and contains 9 diamictites; and Argentina-Peru, which is 150-1000 m-thick and contains <5 diamictites. Few of these 69 Palaeozoic examples appear to be as thick and show as many climatically-related stratigraphic episodes as the PAF.

8. **Conclusions**

The ~1100 m thick succession of the PAF contains 47 diamictites and there is a gradual, progressive evolution upsection in the lithologies of the diamictites, of the interbeds and of the clast types. The diamictites are interpreted as tillites, and their basal surfaces are almost always sharp, recording the change from non-glacial to glacial environments; such environmental switches occur at 25 levels in the PAF. Evidence of periglacial environments occurs at 25 horizons in the PAF; most are at the top of diamictite beds. Sandstone wedges of periglacial origin occur at 23 levels, cryoturbations at 3 levels and frost-shattered stones at 6 levels. The succession in the PAF records 28 glacial, 25 periglacial and 23 non-glacial episodes, thus representing a total of 76 climatically related depositional episodes.

The most complete succession in the PAF occurs on the east coast of Garbh Eileach. Carbon isotope data show no sign of a stratigraphic break at the base of the formation. Additional section is preserved there at three levels – from D1 to D12, from D16 to D18 and from D31 to the base of Member 3.

The PAF in Argyll lies near the middle of a 20-25 km-thick Neoproterozoic sequence. It is underlain by 7 km of largely shallow marine sedimentary rocks and overlain by 6 km of shallow marine and tidal sedimentary rocks. The long-term subsidence rate over these intervals, based on only sparse datings, may have been ca. 100-125 m/Ma. A comparison of the PAF with other thick, relatively complete Phanerozoic and Cryogenian glacial successions suggests that the PAF is exceptional in its combination of formation thickness (~1100 m), the number of climatically-related depositional episodes (76) and the huge thickness of the Neoproterozoic succession within which it lies.

These indicators of relative stratigraphic completeness provide supporting evidence (to the case made in the companion article by Fairchild et al. this volume) that the Garbh Eileach Formation and the base of the PAF on the east coast of Garbh Eileach is a succession without a major break, and so is a candidate for the basal Cryogenian GSSP.

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Figure captions

Fig. 1 Location maps. (a) Outcrop of the Dalradian Supergroup and main localities of the Port Askaig Formation. (b) Main outcrops of the Lossit Limestone, Port Askaig, Bonahaven Dolomite and Jura Quartzite formations from Islay to the Garvellachs. (c) Port Askaig Formation members in the Garvellachs; sea-floor geology inferred from marine bathymetry data.

Fig. 2 Compiled stratigraphic column from the Lossit Limestone to the base of the Jura Quartzite for Islay and the Garvellachs. Locations and sources: lower Lossit Limestone – south of Beannan Buidhe, Islay (new compilation); Garbh Eileach Formation and Members 1-3 – east coast of Garbh Eileach (Spencer 1971, plate 10A); Members 4 and 5 – Port Askaig to Caol Ila and Con Tom (Spencer 1971, plate 10 G, H); Bonahaven Dolomite - north Islay (Spencer & Spencer 1972, fig 2, B, C). Note that the Lossit Limestone of Islay unconformably underlies the PAF, whereas the GEF on the Garvellachs conformably underlies the PAF. Given also chemostratigraphic differences (Fairchild et al. this issue), a gap is shown between the GEF and the Lossit Limestone. Similarly, the exact correlation of the top of Member 3 on the Garvellachs with the base of Member 4 on Islay is unknown (shown as a gap). S=Shallow marine; T=Tidal.

Figure 3. Evolution of the lithologies of the diamictites of the PAF. All photographs are of 50 x 50 cm areas. The lowest diamictite (D7) is a dolomitic siltstone, here showing grey colour because of weathering in the inter-tidal zone; D15 and D19-22 are sand-rich dolomitic siltstones; D26 to D45 are silty arenites with progressively less dolomite. The clast contents show a similar gradual change from dolomite and limestone clasts (D7), to dolomite and crystalline clasts (D15 and D19-22), to crystalline and progressively less dolomite clasts (D26-45). In D26-45 the dolomite clasts weather as holes. These photographs show ten of the diamictite measurement sites plotted in Fig 4 and identified there by red dots.

Figure 4. Evolution of extrabasinal clasts in the diamictites of the PAF, based on a 184 measurements of clasts >1 cm in 50 x 50 cm sized outcrops. The stratigraphic position of each of the 47 diamictites has been plotted according to their percentage height within the 1100 m thickness of the formation. The percentage of extrabasinal clasts is the sum of the granite + quartzite + extrabasinal unknown clasts and excludes intrabasinal clasts (dolomite, limestone, intrabasinal unknown). The red dots are the measurements of the 10 exposures shown in Fig.3. The diagram shows the remarkably gradual change in clast types upwards through the formation.

Figure 5. Carbon isotope profiles of carbonate clasts in diamictites 1 to 12 in relation to bedded carbonates in the Garbh Eileach Formation (GEF). Samples are mainly from east Garbh Eileach, although some close to the base of the PAF were taken from the equivalent sections in Dun Chonnuill and north Garbh Eileach. The standard deviation at each level is also shown for limestones, but not for dolomite as they are not apparently unimodal. A distinct negative carbon isotope anomaly (the Garbh Eileach anomaly) in the GEF is succeeded by values close to zero. The presence of dolomite clasts identical in composition to underlying beds at the top of the GEF and base of the PAF indicates erosion of lateral equivalents of these beds. The presence of limestone and dolomite clasts with negative $\delta^{13}C$ indicates derivation from a deeper level of erosion and the gradual pattern of change shown by the limestone clasts is suggestive of progressive unroofing of the Appin Group carbonate strata during Port Askaig times. Analytical methods and full data listing are given in Fairchild et al. (this issue). Data on bedded carbonate strata include those published in Sawaki et al. (2010).

Fig 6. Examples of the sharp basal contacts of diamictite beds in Member 3 (a-c) and Member 2 (d-f) in the Garvellachs. (a-c) show diamictites which overlie tidal sandstones. (d) D30 overlies a 2m tidal/fluvial sandstone whose base cuts across the sandstone wedge (yellow lines) penetrating the top of D29. (e) The massive, clast-rich D 24 overlies sharply the laminated, clast-poor D23 (ice-rafted?), which rests on tidal/fluvial sandstones. (f) D19 has a sharp, undulating base above a siltstone. (g) D19 overlies, with an irregular contact, a 2 m dolomite breccia (glaciotectonic?); this overlies sharply the Upper Dolomite; the contact of members 1 and 2 of the PAF is here at the top of the Upper Dolomite beneath the dolomite breccia. Localities: a – south coast of Garbh Eileach; b-e – east coast of Garbh Eileach; f – southwest coast of Eileach an Naoimh; g – west cliff of A'Chuli. Scales: a and b – 2 m ruler; c-f – person.

Fig 7. Examples of the upper contacts of diamictite beds in members 3 (a, b, h) and 2 (c, d-g, i) in the Garvellachs. (a, b) Frost-shattered stones in the tops of diamictites; the white outlines enclose the fragments of a former granite boulder (a) and a former quartzite pebble (b). (c) Cross-section view of sandstone downfold structures (cryoturbations) affecting a pebbly sandstone above D26. (d, e) Polygonal sandstone wedges seen looking down on the top surface of D22. (f) An angular breccia (due to frost-shattering?) occurs as a 5cm-thick layer overlying D22, within the outlines of the wedge polygons; for location - see the red rectangle on (e). (g) Cross-sectional view of a sandstone wedge penetrating laminated siltstones, which contain dropstones in this locality; the wedge is capped by a pebble lag (red line) and overlain by more laminated siltstones. (h) View looking down on branching sandstone wedges penetrating the top of D35; both are overlain unconformably by a granitic lag conglomerate. (i) Cross-sectional view of branching sandstone wedges penetrating D26; these are truncated by a bedding plane (red line), above which lies a 50 cm-thick bed of diamictite (labelled D26'). Localities: (a, b) – west coast of Garbh Eileach; (c) – east coast of Garbh Eileach; (d) – southwest coast of Eileach an Naoimh; (e, f) – northeast coast of Eileach an Naoimh; (g) – laminated siltstones at top of Member 2, west coast of Garbh Eileach; (h) – south coast of Garbh Eileach; (i) – east coast of A'Chuli.

Fig. 8. Examples of the many events implied by the periglacial features at the top of D26: (a) measured profile, east coast of Garbh Eileach; (b) stratal column, east coast of A'Chuli. The cryoturbated sandstone bed is present along all of the outcrops for 5km throughout the Garvellachs. See Figure 7 (c) for a photograph of (a) in outcrop. See Figure 7 (i) for a photograph showing the events (1) to (8) of (b) in outcrop.

Fig 9. Comparison of the Lossit Limestone to Disrupted Beds sections of the Garvellachs (left) and Islay (right). Two distinctive units – the Great Breccia and the Disrupted Beds – can be recognized in both localities, but are thicker in the Garvellachs. Diamictites 1 to 12 are missing on Islay: there the Great Breccia rests unconformably on the dolomite bed at the top of the Lossit Limestone (Spencer 1971, fig. 43).

Fig. 10. Correlation of the uppermost beds of Member 1 in the Garvellachs (Fig 1c), showing their subcrop at the unconformity below the Upper Dolomite, which is drawn as a horizontal datum. The section on the east coast of Garbh Eileach contains 18 m of strata that are progressively cut out when traced 5 km to the west. Thus on the east coast the section records more events: three diamictites (D16 to D18), the intervening sandstones and siltstones and a sandstone wedge horizon (top of D18).

Fig. 11. Correlation of the uppermost beds of Member 2 on Garbh Eileach (Fig 1c), showing their subcrop at the unconformity below Member 3, which is drawn as a horizontal datum. The section on the east coast of the island contains 20 m of strata which are progressively cut out when traced 1.5 km to the west. Thus on the east coast the section records several more events: two diamictites (D31, D32), three horizons of sandstone wedges and the unit of 'varved' siltstones.

Fig 12. Outline geological map of the Garvellachs to Jura region superimposed on images of offshore swath bathymetry data and terrestrial airborne radar altimetry data. The relative absence offshore of Quaternary overburden allows the relief of the Dalradian seabed ridges, formed by the more-resistant Dalradian rocks, to be clearly seen. Note the relatively uniform dip angles and directions (35-36 degrees towards the S and SE) in the Garvellach Islands and Jura. Bathymetry data provided courtesy of the Maritime Coastguard Agency's UK Civil Hydrography Programme – Crown Copyright. Terrestrial topography data derived from Intermap Technologies NEXTMap Britain elevation data.

Fig 13. Overviews of thickness data for 33 relatively complete Neoproterozoic glacial successions - the 17 thickest are named. (a) Maximum basal tillite unit thickness versus maximum thickness of underlying Neoproterozoic strata. (b) Maximum tillite-bearing interval thickness versus maximum Neoproterozoic thickness. The data for 32 successions are from the chapters in Arnaud et al. (2011). Where all relevant data are available within a chapter we have accepted the contents of that chapter without further research. For a number of chapters in which key age and / or thickness data are ambiguous or absent we have sought out the most recent authoritative source of the information required (e.g. for NW Tasmania the age / thickness data for the lower Neoproterozoic have been sourced from the Australian Stratigraphic Units Database). In interpreting the contents of the 32 chapters in Arnaud et al. (2011); we have attempted to record in a consistent manner the maximum observed stratal thickness of each of the units reported (Total Neoproterozoic; Sub-tillite Neoproterozoic; Tillite-bearing interval; Basal tillite unit). For the PAF, the values are based on the regional maximum thickness for the Dalradian of 15km given by Stephenson et al. (2013). Note that two important areas are missing due to our lack of overview data: Central and South Australia.

Fig. 14. Summary lithological log of the CIROS-1 drill hole, Ross Sea region, Antarctica. Reproduced from Barrett (1989, fig. 1). Abbreviations: m – marine; d – distal glaciomarine; p – proximal glaciomarine; w – waterlain till (continuous rainout of glacigenic sediment); l – lodgement till (now known as subglacial traction till); O-offshore; N-nearshore; S-shoreface; B-beach; F-fluvial.

Tables

Table 1. Statistics of periglacial features in the Port Askaig Formation. The 47 numbered diamictites in the formation belong to at least 26 groups of diamictites. These groups often show periglacial features at their top: 18 tops have sandstone wedges; 5 tops have frost-shattered clasts; one top has cryoturbations. Most of these tops

show only wedges (13), but at 4 tops there are wedges and frost-shattered clasts and at one top all three features are present. More horizons of periglacial features occur within bedded sedimentary rocks in the Formation: wedges (5), frost-shattered clasts (1), cryoturbations (2) and frozen sedimentary fragments (2). The data from members 1-3 are from the Garvellachs; those from members 4-5 are from Islay. The total of 25 periglacial horizons is the sum of 23 horizons with wedges and two horizons where there are cryoturbations but no wedges (above D26; below D33).

Table 2. Summary of the main climatically-related depositional episodes represented in the Port Askaig Formation. The members, diamictite groups and periglacial horizons in the PAF are shown on Fig 2.

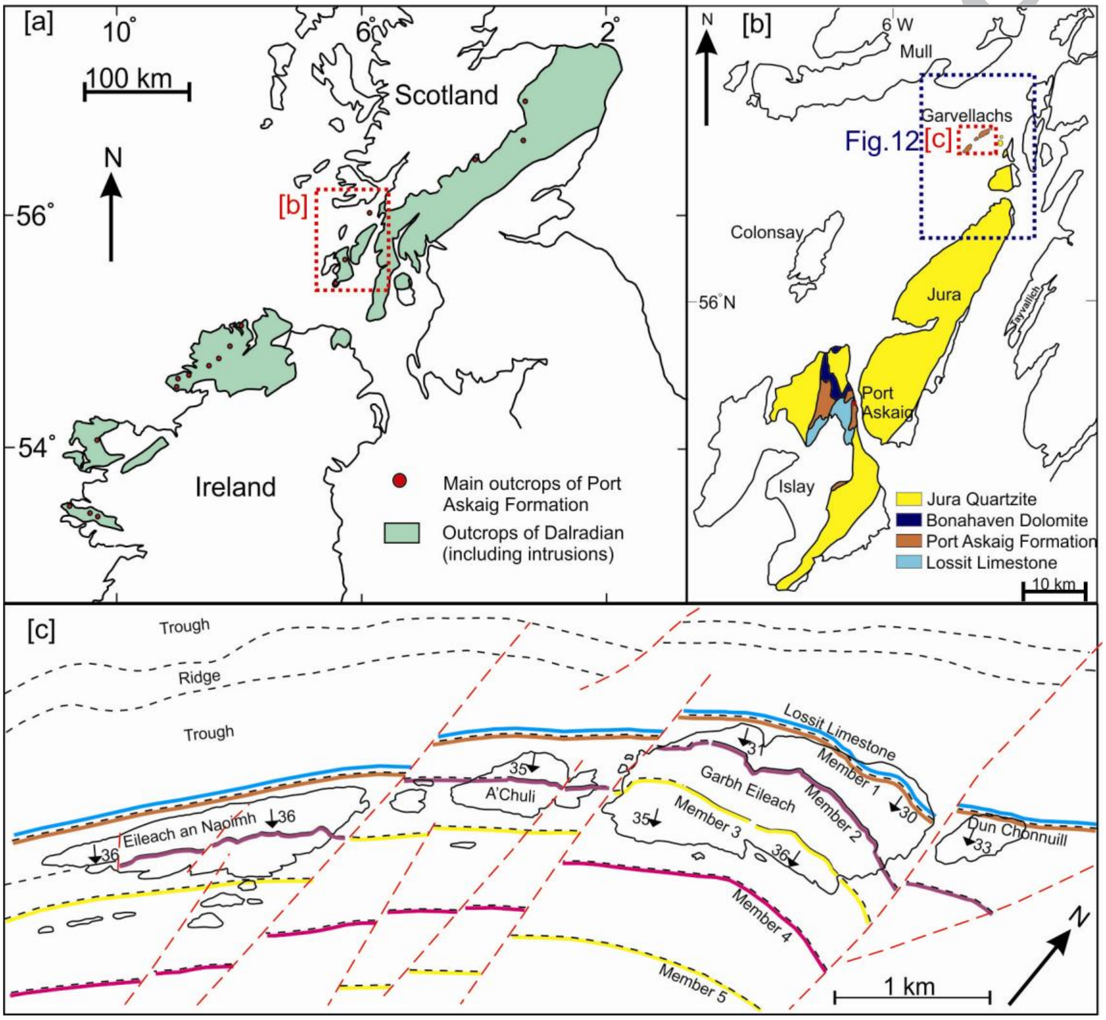
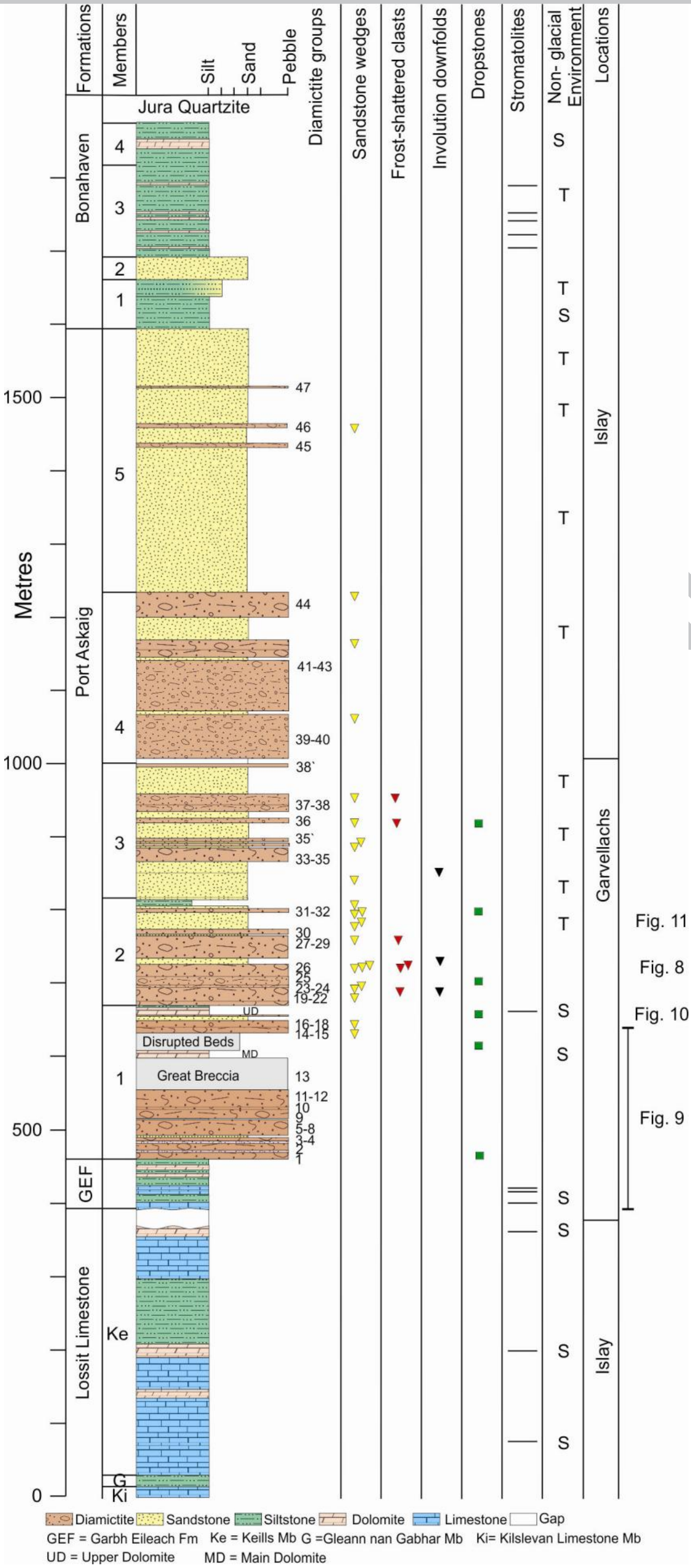


Figure 1



Formations
Members
Silt
Sand
Pebble
Diamictite groups
Sandstone wedges
Frost-shattered clasts
Involution downfolds
Dropstones
Stromatolites
Non- glacial Environment
Locations
Jura Quartzite
Bonahaven
Port Askaig
GEF
Lossit Limestone
Ke
G
Ki
Metres
1500
1000
500
0
Disrupted Beds
Great Breccia
UD
MD
Islay
Garvellachs
Islay
Fig. 11
Fig. 8
Fig. 10
Fig. 9
Diamictite
Sandstone
Siltstone
Dolomite
Limestone
Gap
GEF = Garbh Eileach Fm Ke = Keills Mb G =Gleann nan Gabhar Mb Ki= Kilslevan Limestone Mb
UD = Upper Dolomite MD = Main Dolomite

Figure 2

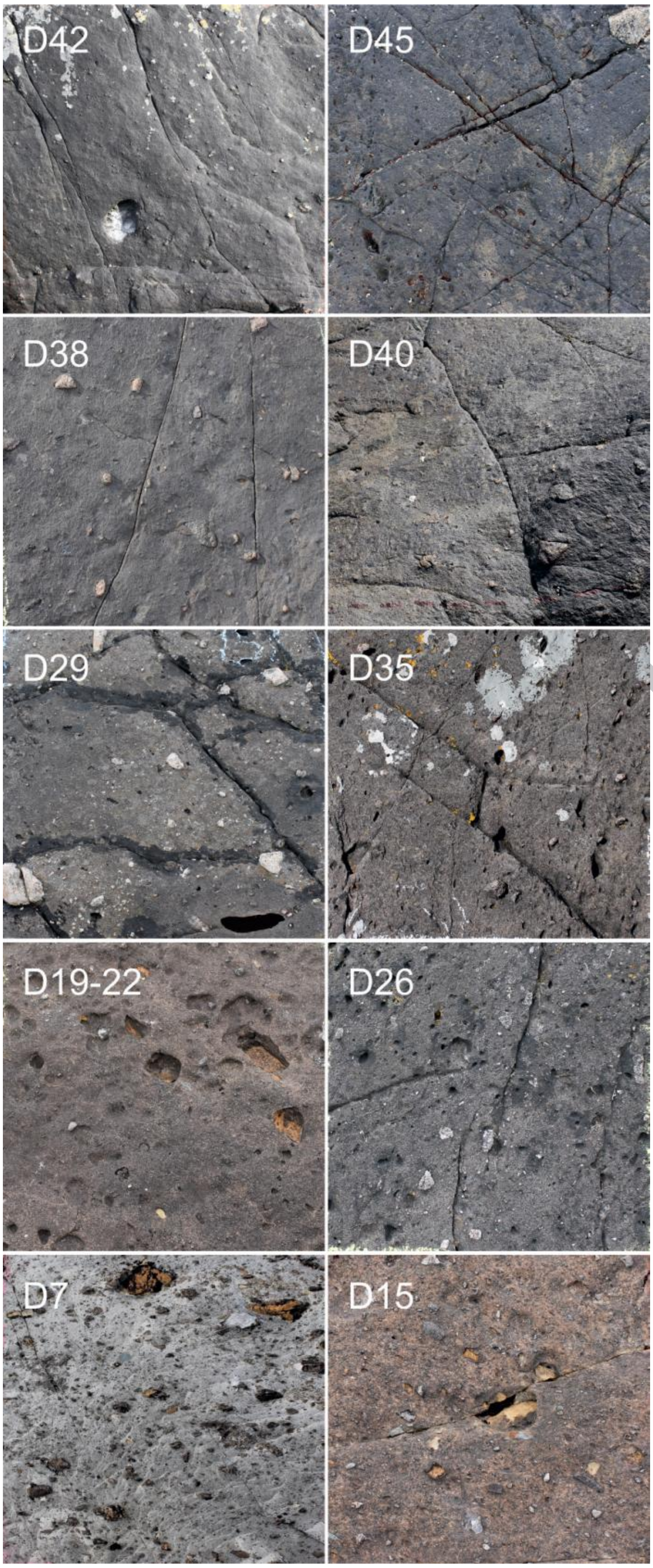


Figure 3

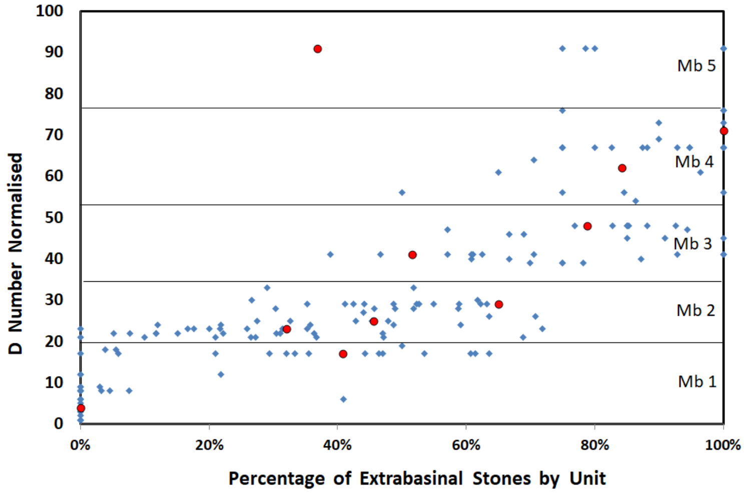


Figure 4

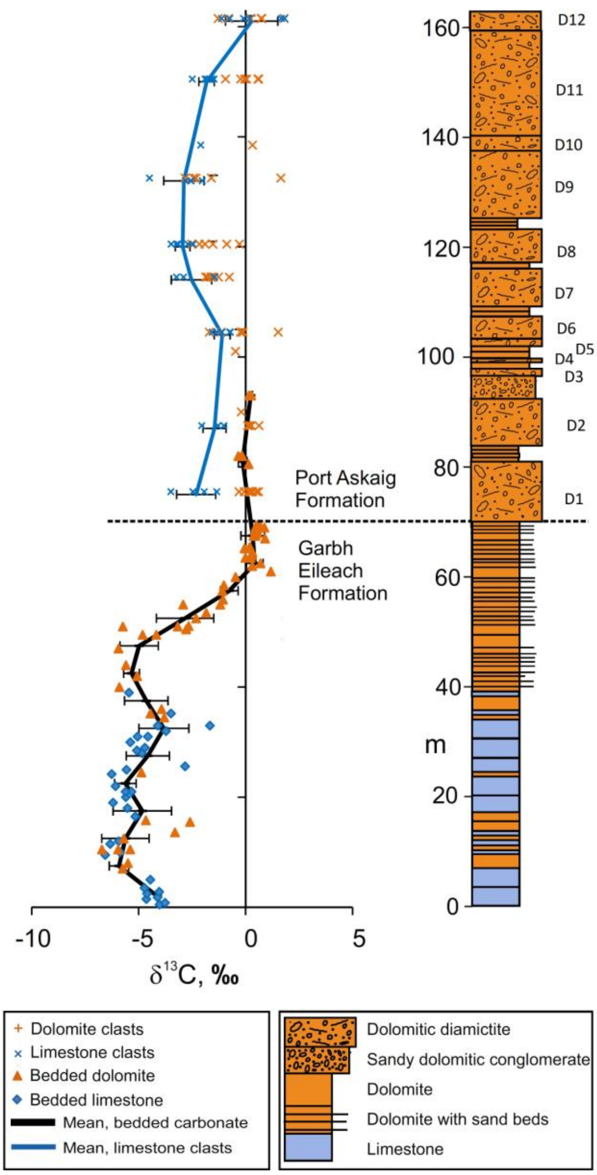


Figure 5

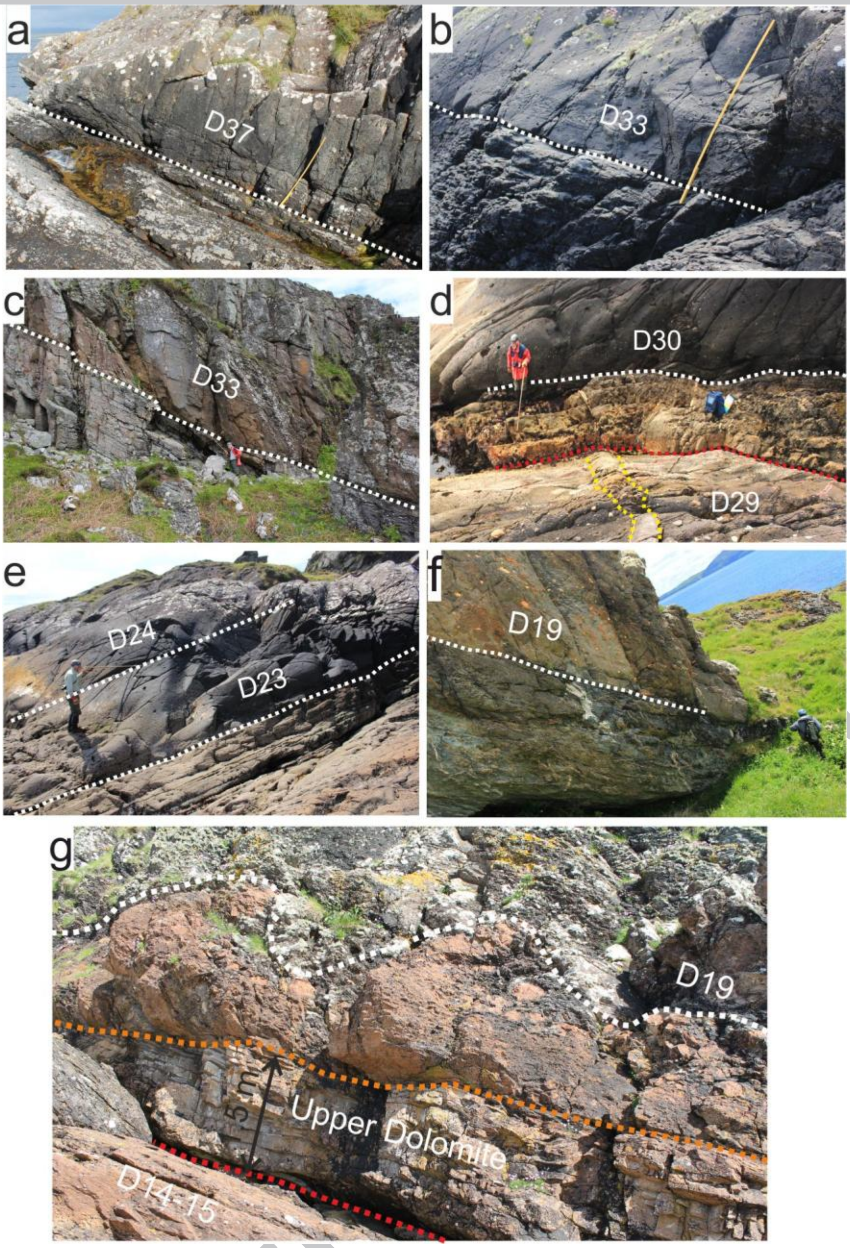

a
D37
b
D33
c
D33
d
D30
D29
e
D24
D23
f
D19
g
D19
5 m
Upper Dolomite
D14-15

Figure 6

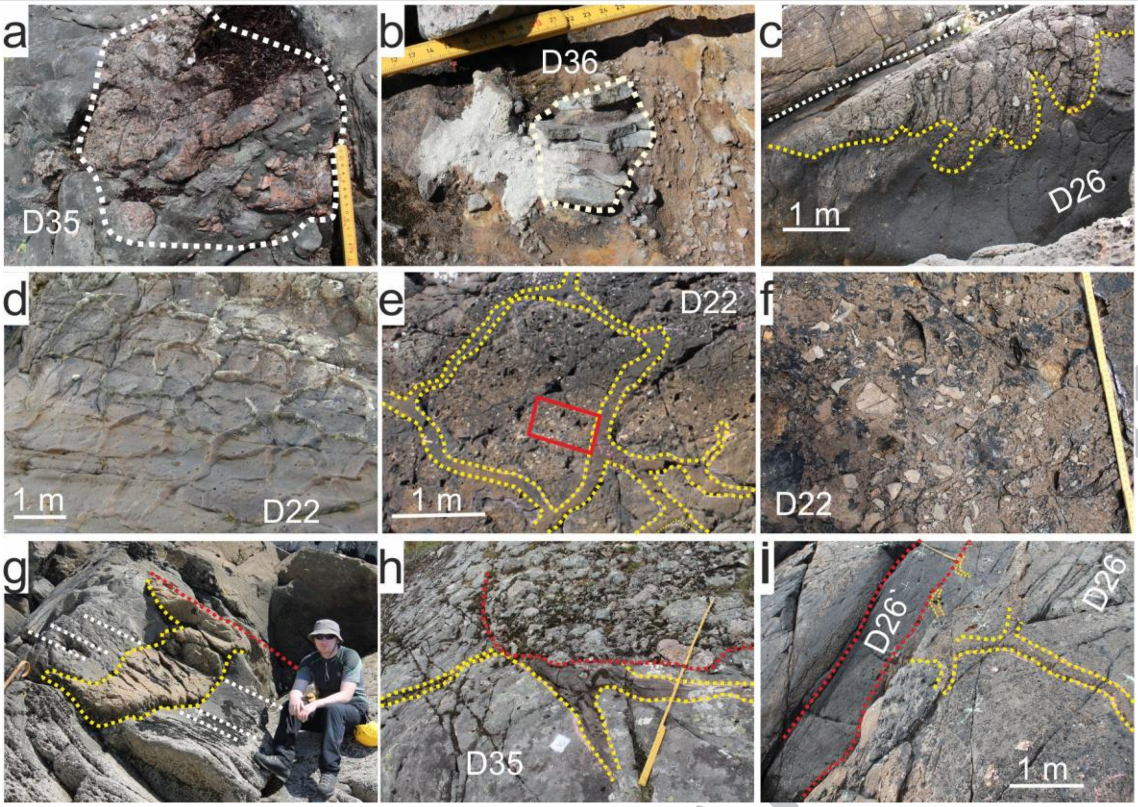


Figure 7

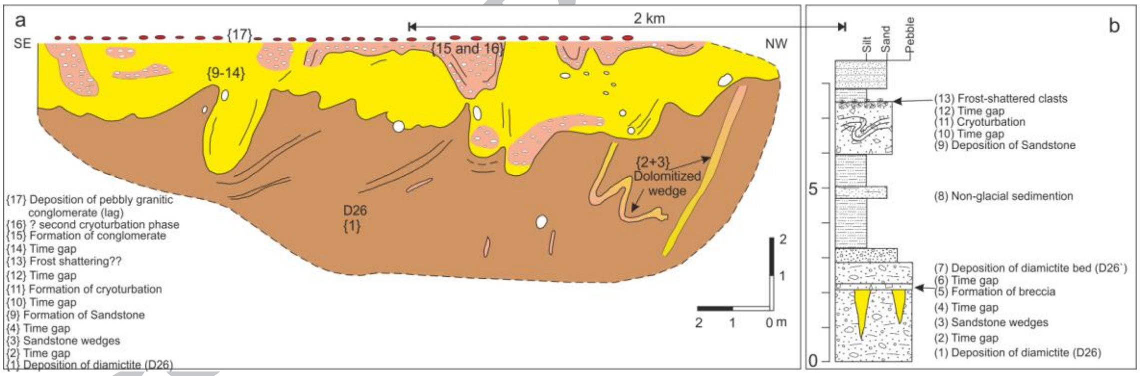


Figure 8

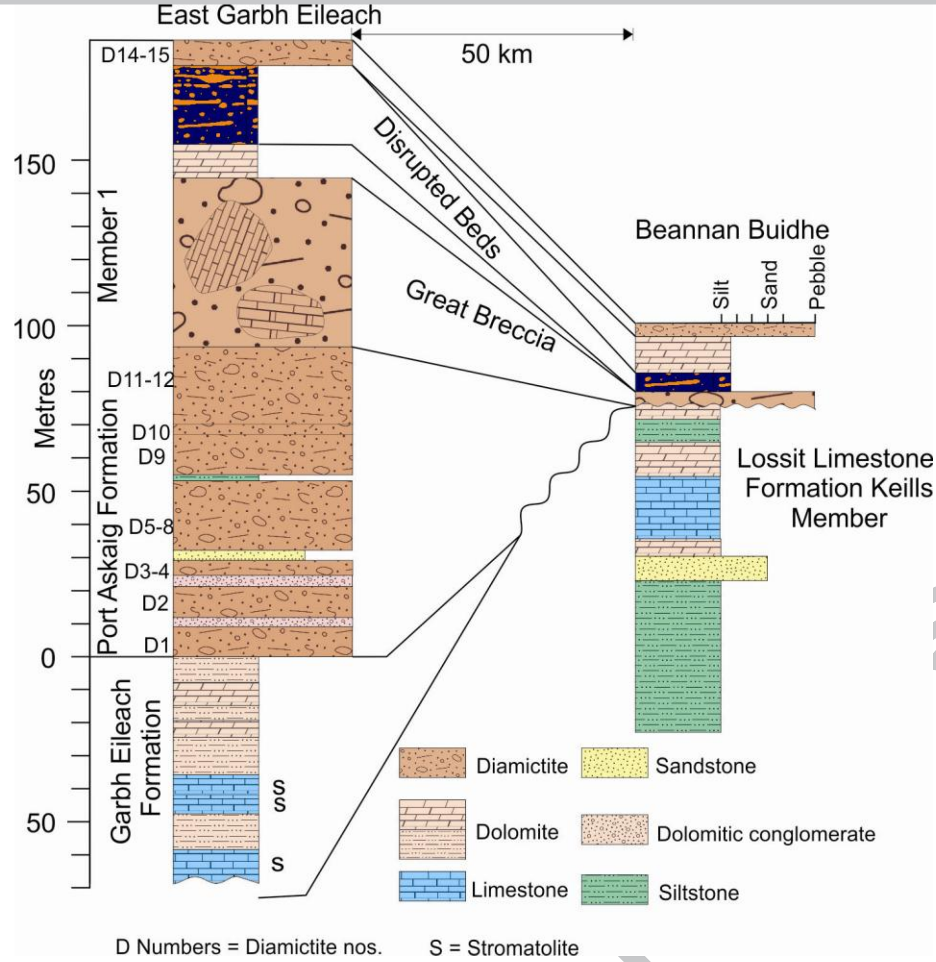

East Garbh Eileach
50 km
D14-15
150
Member 1
100
Metres
D11-12
D10
D9
Port Askaig Formation
50
D5-8
D3-4
D2
D1
0
Garbh Eileach Formation
50
S
S
S
Disrupted Beds
Great Breccia
Beannan Buidhe
Silt
Sand
Pebble
Lossit Limestone Formation Keills Member
Diamictite
Sandstone
Dolomite
Dolomitic conglomerate
Limestone
Siltstone
D Numbers = Diamictite nos.
S = Stromatolite

Figure 9

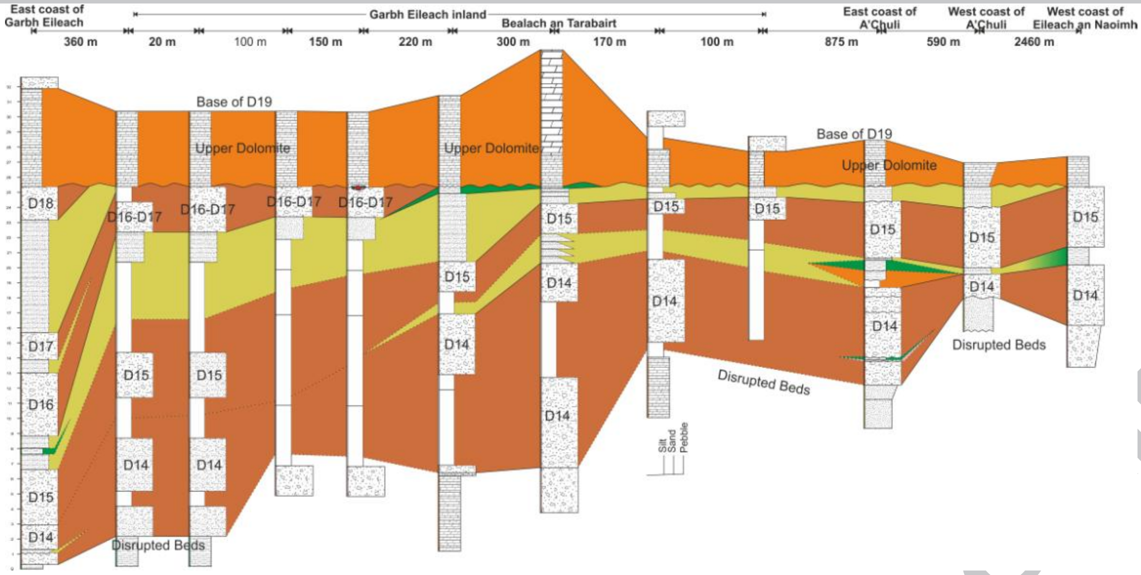


Figure 10

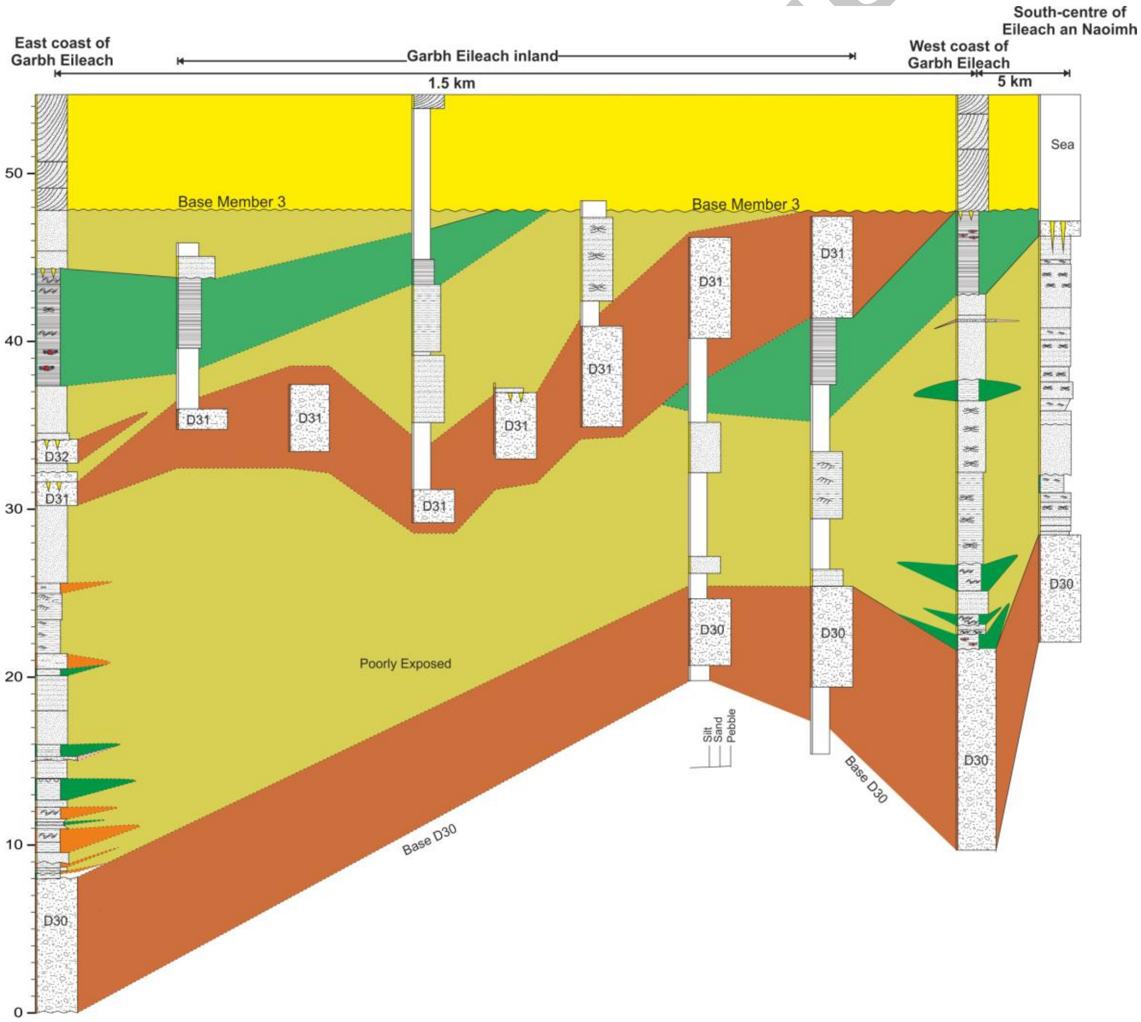


Figure 11

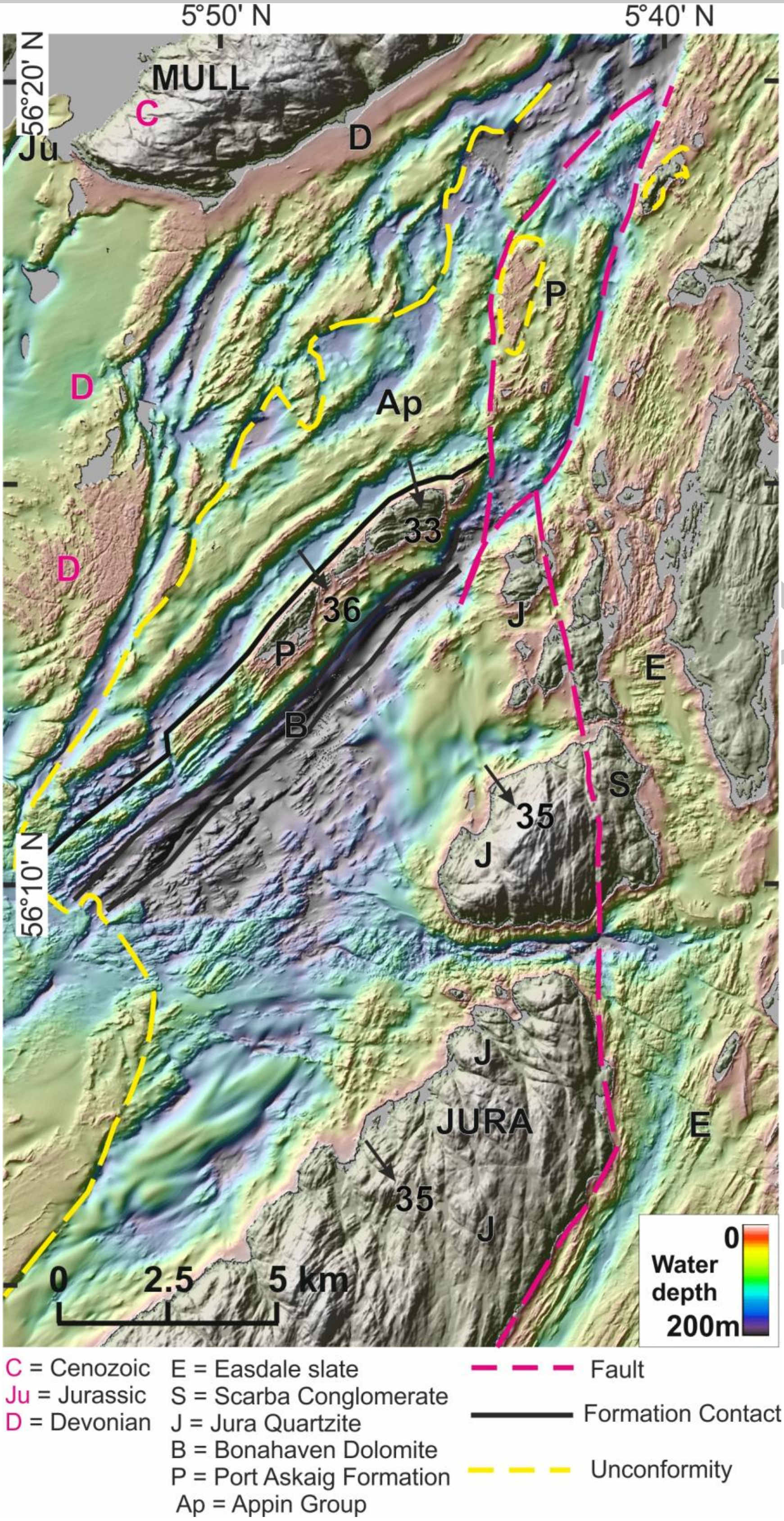

5°50' N
5°40' N
56°20' N
56°10' N
MULL
C
Ju
D
D
D
Ap
P
33
36
P
B
J
E
S
35
J
J
JURA
E
35
J
0
2.5
5 km
Water depth
0
200m
C = Cenozoic
Ju = Jurassic
D = Devonian
E = Easdale slate
S = Scarba Conglomerate
J = Jura Quartzite
B = Bonahaven Dolomite
P = Port Askaig Formation
Ap = Appin Group
Fault
Formation Contact
Unconformity

Figure 12

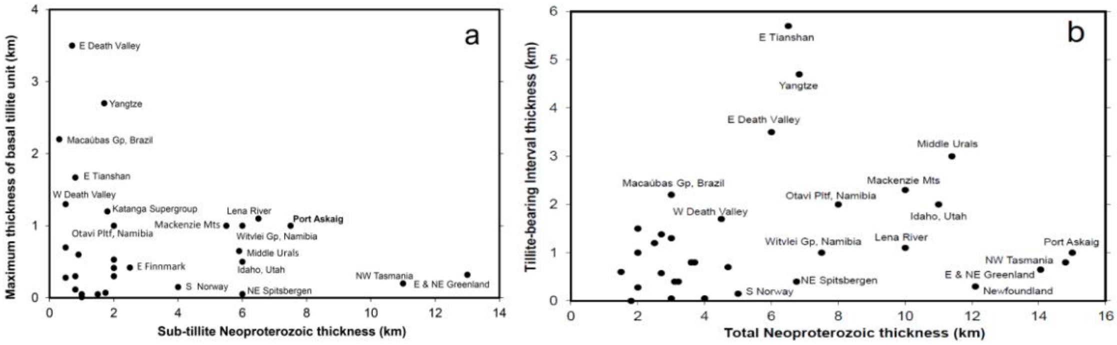


Figure 13

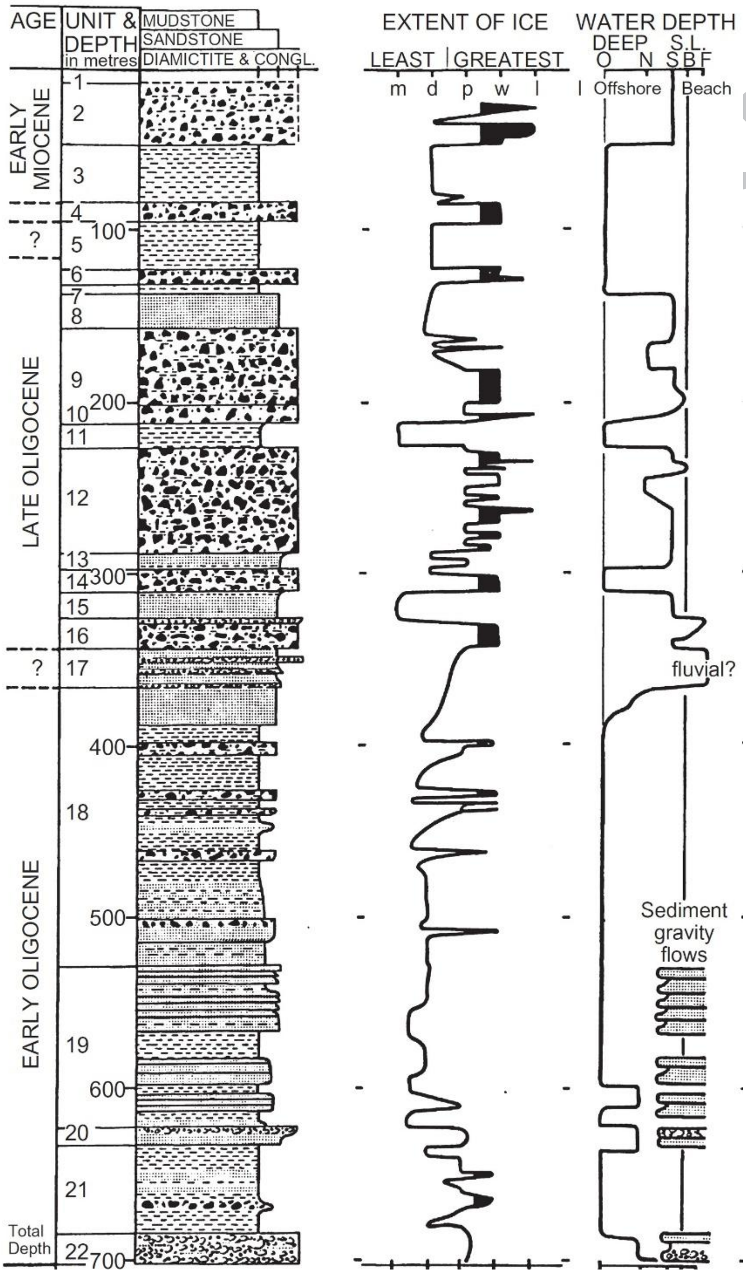


Figure 14

Table 1

Members		1	2	3	4	5	Grand total
Thickness (m)		200	140	180	220	350	ca. 1100
Number of diamictite (D) groups		> 5	9	6	3	3	>26
Number of wedge (W) horizons	W penetrating D	2	7	5	3	1	18
	W penetrating bedded sediments	0	5	0	0	0	5
	Total	**2**	**12**	**5**	**3**	**1**	**23**
Horizons with Frost-shattered clasts (FSC)	FSC on the top of D	0	3	2	0	0	5
	FSC on the top of bedded sediment	0	1	0	0	0	1
	Total	**0**	**4**	**2**	**0**	**0**	**6**
Horizons with involution downfolds (Cr)	Cr at the top of D	0	1	0	0	0	1
	Cr at the top of bedded sediment	0	1	1	0	0	2
	Total	**0**	**2**	**1**	**0**	**0**	**3**
Horizons of frozen sedimentary fragments		0	1	1	0	0	2
Tops of diamictite groups	Horizons with only W	2	4	3	3	1	13
	Horizons with W + FSC	0	2	2	0	0	4
	Horizons with W + FSC + Cr	0	1	0	0	0	1
Total numbers of horizons with periglacial features							**25**

Table 2

Member	Thickness (m)	Diamictite bed numbers	Diamictite groups	Glacial episodes	Periglacial	Non-glacial episodes	Totals, all episodes
5	350	45-47	3	3	1	3	7
4	220	39-44	3	3	3	3	9
3	180	33-38	6	6	6	6	18
2	140	19-32	9	11	13	8	32
1	200	1-18	5	5	2	3	10
Grand totals	Ca. 1100	47	26	28	25	23	76

Suggested sizes of figure when printed: Fig 1 – page width. Fig 2 – column width. Fig 3 – column width. Fig 4 – column width. Fig 5 – column width. Fig 6 – 120mm. Fig 7 – page width. Fig 8 – page width. Fig 9 – 120mm. Fig 10 – page width. Fig 11 – 150mm. Fig 12 – column width. Fig 13 – page width. Fig 14 – column width.